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Development of 873 nm Raman Seed Pulse for Raman-seeded Laser Wakefield Acceleration

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Abstract. By using a Raman-shifted seed pulse coincident with a main driving pulse, laser wakefields can be generated with sub-relativistic intensity, coherent control and high repetition rate in the self-modulated regime. Experimentally, the generation of a chirped Stokes laser pulse by inserting a solid state Raman shifter, $Ba(NO_3)_2$, into a CPA system before the compressor (to suppress self-phase modulation) will be described. We will also report on design, modeling and experimental demonstration of a novel compressor for the Stokes pulse that uses a mismatched grating pair to achieve a near transform-limited seed pulse. Finally, we will describe the design, simulation and current status of Raman-seeded LWFA experiments that use this novel source.

INTRODUCTION

For a chirped Ti:Sapphire laser pulse undergoing Stimulated Raman Scattering (SRS), the dynamics of the scattering most often occur in or near the so called transient regime of scattering. The characteristic time, T_2, that determines the transition from transient to steady-state scattering is given by the time for molecular collisions to cause decoherence. For the solid state SRS shifter $Ba(NO_3)_2$, T_2 is 25 ps. For the LWFA CPA system at UT, CPA pulses of bandwidth 20 nm have a duration of 220 ps. Consequently, SRS in $Ba(NO_3)_2$ occurs in a semi-transient regime.

The steady state raman gain coefficient g_s is given by [2]

$$g_s = \frac{\lambda_p \lambda_s^{\ 2} N}{n_s^{\ 2} hc\pi \Delta\nu_R}\left(\frac{d\sigma}{d\Omega}\right) \tag{1}$$

In the transient regime, the gain coefficient is reduced as the response of the medium decoheres from the laser field. As the pulse duration is reduced far below T_2, SRS asymptotically becomes fluence dependent, whereas at long pulse durations, SRS is intensity dependent. The intensity dependence of SRS at very short pulse durations accounts for the suppression of SRS for ultrashort pulses. Self-phase modulation (SPM) is also intensity dependent. As a consequence, SPM is the dominant mechanism for shifting spectral energy to the sideband frequency. As recent work has shown, using chirped pulses for SRS suppresses SPM and subsequent compression yields ultrashort pulses [3]. However, there are issues with compressing a chirped Raman shifted pulse as will be discussed later.

A compressed, energetic, frequency shifted ultashort laser pulse has many applications including , but not limited to a low group velocity walkoff, spectrally distinct probe, a secondary pump or probe pulse for harmonic generation experiments where distinction of harmonics from the fundamental is complicated when using second harmonic light, and low energy laser wakefield acceleration (LWFA) using the Raman-seeded LWFA (RS-LWFA) mechanism.

Following the work of Fisher and Tajima, recent PIC simulations have shown that by use of a Raman-shifted seed pulse, a low energy LWFA can be constructed that traps and accelerates electrons from the background plasma [1,4]. The seed pulse produces a beat with the fundamental that can create a controllable background plasma wave level to seed the LWFA mechanism as shown in figure 1.

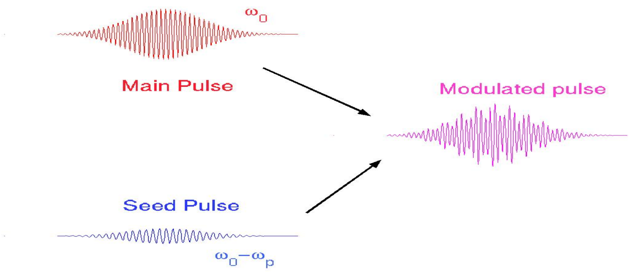

Figure 1. Schematic showing production of a Raman-seeded laser pulse.

Placing the seed at the front of the pump pulse increases the interaction length for forward Raman scattering (FRS) and gives a controlled wakefield seed that replaces ionization and pulse shape gradients for the growth of the FRS instability. In fact, by reducing the fluctuations in the seed for FRS by using a Raman seed of sufficient energy produced from a portion of the fundamental and by reducing the overall level of Raman gain needed in plasma, the FRS instability can be stabilized.

A low energy Raman-seeded LWFA would allow the repetition rate of the laser to be increased giving a higher overall current of electrons which is of interest in applications such as a medical accelerator [5]. An additional advantage of RS-LWFA is the possibility of coherent control of the wakefield. By suitable delay of the Raman seed, the phase of the plasma wave relative to the laser driver can be arbitrarily set in recent PIC sims, see figure 2 [4]. The dephasing length of a LWFA can be overcome in a two-stage LWFA where the phase of the seed has been changed so that the second stage accelerator places the accelerated electrons back into the accelerating phase of the plasma wave.

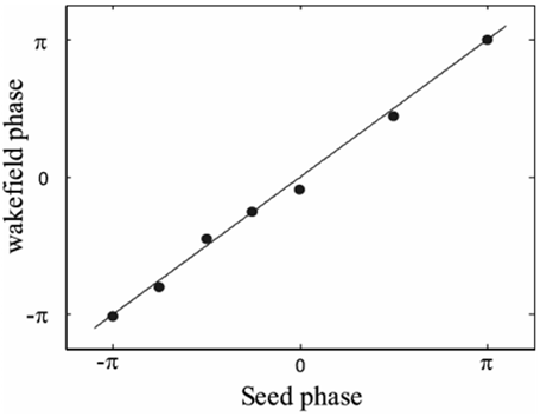

Figure 2. Wakefield phase plotted versus seed phase showing the possibility of coherent control.

The construction of a suitable seed pulse for RS-LWFA is vital if the predictions of simulation: coherent control, stability, and low energy, efficient particle trapping are to become reality.

PRODUCTION OF STOKES SHIFTED PULSES IN $BA(NO_3)_2$

Recent advances in solid-state Raman shifters have led to the production of crystals with high Raman gain of suitable optical quality [3]. Barium nitrate ($Ba(NO_3)_2$) is a uniaxial crystal with many properties that make it desirable for SRS. A Raman active mode at 1047.3 cm^{-1} with a narrow linewidth of 0.4 cm^{-1} gives a shift of 800 nm to 873 nm in the first Stokes sideband. The narrow linewidth yields a large Raman gain as equation 1 shows. A shift of 73 nm is useful as the bandwidth of a 30 nm FWHM input pulse and the bandwidth of the shifted pulse can be considered distinct. Also, the plasma frequency corresponding to the beat frequency between fundamental and Stokes gives a plasma density of 1.2×10^{19} cm^{-3} which is desirable as it is accessible from a gas jet or in a plasma channel at the facility at UT.

At UT Austin, up to 40 mJ is sent into a 5 cm long Barium Nitrate crystal after a telescope to reduce the beam size to yield a suitable intensity. The output is separated from the fundamental by the use of two dichroic dielectric mirrors. A long pass filter, RG850, of thickness 3 mm is also used to get a Raman shifted beam with a high contrast of Stokes light to residual fundamental light. Efficiencies as high as 20% have been measured correcting for losses due to filters such as the RG850, figure 3. The beam profile is not uniform and exhibits spiky behavior, figure 4. A recent method has been devised that yields low energy, 100 μJ, beams with uniform beam profiles, figure 4, as will be described in a future paper. This beam is promising as it will allow amplification in Raman amplifier or a Ti:Sapphire power amplifier where the gain cross section is still appreciable at 873 nm. A clean profile Raman shifted CPA beam has recently been produced and further progress including compression is currently being pursued.

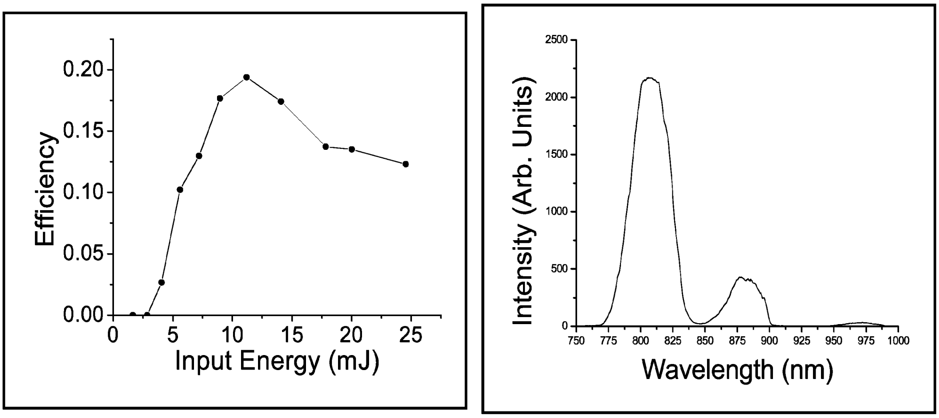

Figure 3. Efficiency of first Stokes conversion and spectrum of beam at output of $Ba(NO_3)_2$ crystal.

Figure 4. Beam images of first Stokes beam. Left, output of crystal. Right, cleaned up 873 nm beam.

Compression of a frequency shifted CPA beam is non-trivial. The operation of CPA systems in the simplest description relies on the compressor undoing the stretch that the stretcher has imposed upon the beam. However, shifting the frequency of the light between the stretcher and compressor breaks the symmetry between the stretcher and the compressor. Previous groups have compressed a Raman shifted CPA beam, but found the compression in theory and practice to be far from the transform limit [3]. ZEMAX ray-trace simulations of our CPA system confirm that sending the Stokes shifted light into the pulse compressor after optimizing its angle and grating separation gives a distorted pulse. Figure 6 shows a beam of 30 nm FWHM after going through the full CPA system with 1200 line/mm gratings in stretcher and compressor. The beam is third order limited with large wings and nonlinear residual frequency chirp.

An alternative compression solution was needed to yield pulses suitable for RS-LWFA. It was discovered through ray-trace simulation that using gratings of lower dispersion of line density 830.8 line/mm gave fourth-order limited pulses with half the pulse duration previously achievable and four times the peak power, figure 5. To make the simulation reality, a test grating was purchased and the efficiency of diffraction was measured. Fortunately, the gratings were > 85 % efficient, available in large blank sizes, and therefore suitable for a pulse compressor. The gratings have been purchased and the compressor built. The test of compression is currently being conducted. It is of interest to note that a 1800 line/mm compressor was previously built with gratings already available in the lab and compression to ~ 1 ps was achieved. The compression was consistent with ZEMAX simulation, verifying its utility, preliminary experiments were planned, but compression was not sufficient for RS-LWFA. The optimized grating line density gratings arrived shortly thereafter and the 1800 line/mm compressor was abandoned. Future compression and implementation of the RS-LWFA is currently being pursued and is very promising.

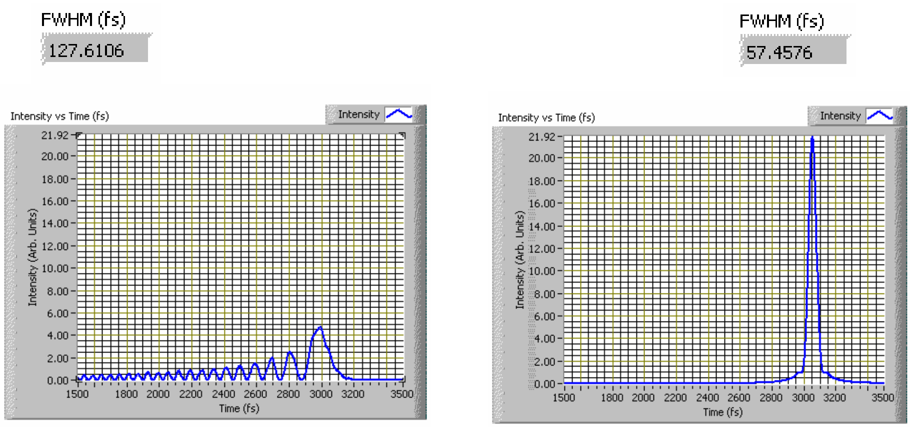

Figure 5. Compression of first Stokes beam from ray-tracing analysis. Intensity versus time is plotted. Left is 1200 line/mm compressor and stretcher. On the right, the compressor uses 830.8 line/mm gratings. Note the improvement in compression on the right with a four times greater peak intensity.

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